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9.5 Analysis of material features for rendering tasks

At the current stage of the development of three-dimensional graphics, a significant attention is paid to the formation of highly realistic images. At the same time, the color intensity [419, 420] and the memory address for the memorization are calculated for each point of the image.

During the determination of color intensity I of a pixel [421], the ambient, diffuse and specular color components are taken into account

$$I = k_a I_a + k_d I_{so}(\vec{L} \cdot \vec{N}) + k_s I_{so} \cdot f_r,$$

where k_a - ambient lighting coefficient, I_a - ambient light intensity, k_d - diffuse reflection coefficient, I_{so} - light source intensity, $\vec{L}, \vec{N}$ - illumination and normal vector respectively, k_s - specular reflection coefficient, f_r - bidirectional reflectance distribution function (BRDF) value.

Ambient color component [421] corresponds to the light reflected from the external environment objects. The diffuse component of color [421] represents the light reflected from the surface in different directions and determines the visibility of the object. The specular component of color [421] determines the reproduction of specular glares on the surface of the object.

It is important to note that $k_d + k_s = 1$ [422]. The ratio of k_d and k_s is different for each material. When forming three-dimensional images, it is important to know these values. For example, ideal metals that are current conductors are characterized by the presence of only specular reflection of light [423]. Ideal diffuse surfaces reflect light uniformly in all directions and do not contain specular reflections. Most materials combine features of both types of light reflection.

A high k_s value [424] is typical for polished metals (0.8-1), metals (0.6-0.7), liquids (0.7-1), shiny paints (0.6-0.7), processed gemstones (0.8-0.9). A high value k_d [424] is typical for fabrics (0.6-0.8), matte plastics (0.7 – 0.8), matte paints and glass (0.8),

unpolished cellulosic materials (0.6 – 0.7). Building materials, skin, ordinary plastics have approximately equal values of k_d and k_s.

During the formation of three-dimensional images, the following formula is used for the specular component of color [421]

$$k_s \cdot I_{so} \cdot f_r .$$

BRDF (f_r) [421, 425-430] is a function that determines the ratio of the light reflected from the light source to the observer. The two main types of BRDF are empirical and physically-based BRDFs. Empirical BRDFs usually depend on the illumination vector $\vec{L}$, the vector to the observer $\vec{V}$, and the shininess coefficient of the surface n.

n [421] determines the degree of concentration of specular reflection on the surface and varies from 1 to 1000. For shiny surfaces [422] n approaches 1000. Such materials include polished metals (100-1000), metals (50-600), liquids (100- 1000), processed gemstones (100-600), glossy and semi-gloss paints (50-300). For rough and matte surfaces, n takes values, close to zero. Materials with a low n value are fabrics (5-50), plastics (5-80), skin (5-50), building materials (5-20), ceramics (5-80), unpolished cellulosic materials (5-30).

More complex physically accurate BRDFs [421, 431, 432] take into account the microfacet structure of the material surface. As a rule, the distribution function of microfacets includes the calculation of the surface roughness parameter α. $\alpha = 0$ means that the surface is smooth and does not contain microfacets. A small value of α [433] is characterized by the predominant orientation of the microfacet normals in the direction of light reflection. At large values of the parameter α [433], the light reflection becomes more and more uniformly distributed over the entire surface, if $\alpha = 1$, the reflection is completely uniform.

Polished metals (0.01-0.03), metals (0.1-0.4), still liquids (0.01-0.3), processed gemstones (0.02-0.25), clean glass (0.01-0.05), polished wood (0.02- 0.05), shiny paints (0.05-0.3) have a small roughness [424]. Average roughness is typical for plastics (0.05-0.5), ceramic surfaces (0.2-0.4), skin (0.2-0.7), matte paints (0.1-0.7).

The surfaces of fabrics (0.25-0.8), building materials (0.3-1), cellulose materials (0.3-0.8) are rough [424].

Table 1 [422, 424] shows typical values of surface shininess coefficient n, surface roughness α, diffuse reflection coefficient k_d, specular reflection coefficient k_s for ideal mirror and ideal diffuse surfaces. An ideal mirror surface is characterized by maximum values of n, k_s, and minimum values of α, k_d. . At the same time, an ideal diffuse surface is characterized by maximum values of α, k_d, and minimum values of n, k_s.

Table 1.

The values of surface shininess coefficient, roughness, diffuse and specular reflection coefficients for ideal surfaces

Material	n	α	k_d	k_s
Ideal specular surface	1000	0	0	1
Ideal diffuse surface	0	1	1	0

Table 2 [422, 424] shows the values of n, α, k_d, k_s for polished metals. Silver, gold, iridium, bronze, platinum, chrome are characterized by the biggest n value. A typical range of α values for polished metals is 0.01 - 0.03.

Table 2.

The values of surface shininess coefficient, roughness, diffuse and specular reflection coefficients for polished metals

Material	n	α	k_d	k_s
Polished silver	700	0.01 - 0.03	0.03	0.97
Polished iridium	700-1000	0.01 - 0.03	0.08	0.92
Polished gold	650	0.01 - 0.03	0.05	0.95
Polished bronze	600	0.01 - 0.03	0.16	0.84
Polished platinum	600-900	0.01 - 0.03	0.09	0.91

Continuation of Table 2.

Material	n	α	k_d	k_s
Polished chrome	600-800	0.01 - 0.03	0.1	0.9
Polished copper	400	0.01 - 0.03	0.15	0.85
Polished cobalt	400-700	0.01 - 0.03	0.16	0.84
Polished nickel	300-700	0.01 - 0.03	0.14	0.86
Polished titanium	300-600	0.01 - 0.03	0.17	0.83
Polished stainless steel	200-500	0.01 - 0.03	0.18	0.82
Polished brass	200-400	0.01 - 0.03	0.19	0.81
Polished zinc	100-300	0.01 - 0.03	0.23	0.77
Polished tin	50-200	0.01 - 0.03	0.24	0.76
Polished aluminum	70-150	0.01 - 0.03	0.1	0.9
Polished magnesium	50-150	0.01 - 0.03	0.21	0.79

Table 3 [422, 424] shows the values of n, α, k_d, k_s for unpolished metals. Slightly smaller values of n (up to 600), k_s (about 0.7) and larger values of α (0.1 – 0.4) are typical for unpolished metals.

Table 3.

Values of shininess coefficient, surface roughness, diffuse and specular reflection coefficients for metals

Material	n	α	k_d	k_s
Chrome	600	0.1 - 0.2	0.29	0.71
Silver	400	0.1 - 0.25	0.3	0.7
Gold	400	0.1 - 0.3	0.3	0.7
Iridium	300-600	0.1 - 0.3	0.31	0.69
Brass	218	0.1 - 0.3	0.39	0.61
Bronze	200	0.1 - 0.3	0.39	0.61
Platinum	200-400	0.1 - 0.3	0.33	0.67

Continuation of Table 3.

Material	n	α	k_d	k_s
Titanium	100-300	0.1 - 0.3	0.39	0.61
Nickel	100-300	0.1 - 0.3	0.36	0.64
Copper	100	0.1 - 0.3	0.4	0.6
Cobalt	100-300	0.1 - 0.35	0.36	0.64
Tin	77	0.1 - 0.35	0.41	0.59
Stainless steel	50-200	0.1 - 0.35	0.42	0.58
Zinc	50-150	0.1 - 0.35	0.43	0.57
Magnesium	20-50	0.1 - 0.4	0.45	0.55
Aluminum	10-50	0.1 - 0.4	0.45	0.55

Table 4 [422, 424] shows the values of n, α, k_d, k_s for plastics and elastomers. The most shiny are transparent plastic (acrylic), polycarbonate, glossy plastic (n is 10 - 80, k_s has a value of 0.6 - 0.7). Polypropylene, matte plastic, rubber have small values of n (1 – 20), k_s (0.2). The roughness of these materials is average (values around 0.4-0.5).

Table 4.

Values of shininess coefficient, surface roughness, diffuse and specular reflection coefficients for plastics and elastomers

Material	n	α	k_d	k_s
Transparent plastic (acrylic)	30-80	0.05 - 0.15	0.37	0.63
Polycarbonate	20-50	0.05 - 0.15	0.38	0.62
Glossy plastic	10-50	0.05 - 0.2	0.33	0.67
PET (polyethylene terephthalate)	10-40	0.05 - 0.2	0.39	0.61
ABS plastic	10-40	0.1 - 0.3	0.52	0.48
PVC (polyvinyl chloride)	10-30	0.1 - 0.3	0.52	0.48

Continuation of Table 4.

Material	n	α	k_d	k_s
Plastic film	10-30	0.05 - 0.2	0.7	0.3
Polystyrene	5-25	0.1 - 0.4	0.55	0.45
Polypropylene	5-20	0.1 - 0.4	0.8	0.2
Epoxy resin	5-20	0.1 - 0.4	0.52	0.48
Matte plastic	1-10	0.2-0.5	0.78	0.22
Rubber	5-20	0.5-0.7	0.81	0.19

Table 5 [422, 424] shows the values of n, α, k_d, k_s for fabrics. A characteristic feature of fabrics is high values of α and k_d. Accordingly, n is insignificant. In particular, microfiber, fleece, and felt have the highest roughness (0.4–0.8). Their k_d and n values are 0.8 and 1–10, respectively. Velvet, silk, satin are more shiny materials and have a value of n 10-50.

Table 5.

Values of shininess coefficient, surface roughness, diffuse and specular reflection coefficients for fabrics

Material	n	α	k_d	k_s
Velvet	20-50	0.4 - 0.8	0.82	0.18
Latex	20-50	0.25 - 0.5	0.75	0.25
Silk	10-30	0.25 - 0.6	0.7	0.3
Sateen	10-30	0.2 - 0.6	0.66	0.34
Atlas	10-30	0.2 - 0.6	0.63	0.37
Velor	10-30	0.4 - 0.6	0.71	0.29
Chiffon	10-30	0.3 - 0.5	0.7	0.3
Jacquard	10-30	0.25 - 0.5	0.67	0.33
Jeans	5-20	0.3 - 0.7	0.77	0.23
Knitwear	5-20	0.3 - 0.7	0.77	0.23

Continuation of Table 5.

Material	n	α	k_d	k_s
Cotton	5-20	0.3 - 0.8	0.8	0.2
Flax	1-10	0.3 - 0.8	0.79	0.21
Wool	1-10	0.3 - 0.8	0.79	0.21
Polyester	1-10	0.3 - 0.8	0.76	0.24
Nylon	1-10	0.3 - 0.6	0.74	0.26
Fleece	1-10	0.4 - 0.8	0.81	0.19
Microfiber	1-10	0.4 - 0.8	0.76	0.24
Felt	1-10	0.4 - 0.8	0.82	0.18

Table 6 [422, 424] shows the values of n, α, k_d, k_s for different types of skin.

The skin is characterized by a relatively low shininess (n is 5-50, the highest value is for wet, oily skin and skin with makeup) and moderate roughness (0.2-0.7, the roughest is skin with problems and dry skin).

The values of the coefficients k_d, k_s are approximately similar with a predominance of k_d (0.55 - 0.7).

Table 6.

Values of shininess coefficient, surface roughness, diffuse and specular reflection coefficients for different types of skin

Material	n	α	k_d	k_s
Moist skin	20-50	0.2 - 0.4	0.67	0.33
Oily skin	20-40	0.2 - 0.3	0.61	0.39
Skin with makeup	10-30	0.1 - 0.3	0.55	0.45
Normal skin	10-25	0.3 - 0.6	0.68	0.32
Skin with problems (acne, scars)	5-15	0.5 - 0.7	0.72	0.28
Dry skin	5-15	0.4 - 0.7	0.72	0.28

Table 7 [422, 424] shows the values of n, α, k_d, k_s for liquids. Clean and still liquids have high value of n, k_s and insignificant roughness α. For example, for clean still water $n=1000$, $k_s=0.96$, $\alpha=0.01-0.05$. At the same time, opaque and mobile liquids are rougher and less shiny. For example, for water with waves $n=200-500$, $k_s=0.84$, $\alpha=0.05-0.3$. For muddy water, the values are as follows: $n=100-200$, $k_s=0.68$, $\alpha=0.1-0.3$.

Table 7.

Values of shininess coefficient, surface roughness, diffuse and specular reflection coefficients for liquids

Material	n	α	k_d	k_s
Clean still water	1000	0.01 - 0.05	0.04	0.96
Nail polish	500-1000	0.1 - 0.25	0.27	0.73
Oil (vegetable, motor)	500-800	0.05 - 0.1	0.26	0.74
Alcohol (ethanol)	300-600	0.01 - 0.05	0.1	0.9
Ice	300-500	0.05 - 0.15	0.13	0.87
Water with waves	200-500	0.05 - 0.3	0.16	0.84
Juice (clear)	200-400	0.05 - 0.1	0.17	0.83
Sweet drinks (carbonated)	200-400	0.05 - 0.1	0.17	0.83
Blood	100-300	0.05 - 0.3	0.24	0.76
Honey	100-300	0.1 - 0.3	0.24	0.76
Soap or shampoo solutions	100-300	0.1 - 0.3	0.23	0.77
Juice (opaque)	100-300	0.1 - 0.3	0.29	0.71
Ink	100-300	0.1 - 0.3	0.3	0.7
Muddy water	100-200	0.1 - 0.3	0.32	0.68
Milk	50-150	0.1 - 0.3	0.33	0.67
Coffee	50-150	0.1 - 0.3	0.33	0.67
Tea	50-150	0.1 - 0.3	0.33	0.67

Table 8 [422, 424] shows the values of n, α, k_d, k_s for various paints and varnishes. Materials such as glossy paint, clear varnish, automotive and enamel paints have a fairly high value of n (80-300) and k_s (0.7-0.8) and a small value of α (0.05-0.3). Paints of a different type, such as matte, water-based, wall paint, are characterized by lower values of n (10-70), a significant proportion of diffuse light reflection k_d (0.5-0.8), high roughness (0.3-0.7).

Table 8.

Values of shininess coefficient, surface roughness, diffuse and specular reflection coefficients for paints and varnishes

Material	n	α	k_d	k_s
Varnish (transparent)	100-300	0.05 - 0.15	0.22	0.78
Glossy paint	100-200	0.05 - 0.15	0.26	0.74
Automotive paint	100-200	0.05 - 0.3	0.3	0.7
Enamel paint	80-200	0.05 - 0.15	0.27	0.73
Semi-gloss paint	50-150	0.1 - 0.3	0.43	0.57
Paint for metal	50-150	0.1 - 0.3	0.38	0.62
Oil paint	50-150	0.1 - 0.4	0.39	0.61
Paint for wood	30-100	0.1 - 0.4	0.4	0.6
Paint for plastic	20-80	0.1 - 0.3	0.39	0.61
Wall paint (exterior)	20-70	0.3 - 0.6	0.47	0.53
Acrylic paint	20-70	0.1 - 0.3	0.42	0.58
Latex paint	20-50	0.2 - 0.5	0.44	0.56
Matte paint	10-50	0.3 - 0.7	0.76	0.24
Wall paint (interior)	10-50	0.3 - 0.5	0.49	0.51
Water-based paint	10-40	0.3 - 0.5	0.48	0.52

Table 9 [422, 424] shows the values of n, α, k_d, k_s for stones. The high smoothness of the surface is characteristic of processed gemstones. Therefore, the

value of α is minimal (0.02 – 0.05 for ruby and emerald), and the shininess is high (n is 600 for ruby and emerald). Accordingly, k_s is also significant (about 0.85). Common stones, such as unpolished marble and granite, are less shiny ($n = 20 - 60$) and rougher ($\alpha = 0.1 - 0.25$).

Table 9.

Values of shininess coefficient, surface roughness, diffuse and specular reflection coefficients for stones

Material	n	α	k_d	k_s
Emerald (processed)	600	0.02 - 0.05	0.14	0.86
Ruby (processed)	600	0.02 - 0.05	0.14	0.86
Obsidian (worked)	300	0.02 - 0.05	0.19	0.81
Turquoise (processed)	100	0.05 - 0.15	0.22	0.78
Jade (processed)	100	0.05 - 0.15	0.22	0.78
Polished marble	50-200	0.02 - 0.1	0.19	0.81
Polished granite	50-200	0.02 - 0.1	0.19	0.81
Marble	30-60	0.1 - 0.25	0.32	0.68
Granite	20-50	0.1 - 0.25	0.32	0.68

Table 10 [422, 424] shows the values of n, α, k_d, k_s for building materials. The surfaces of most building materials are non-glossy, have average (0.3 – 0.7 for concrete and brick) or high roughness (0.5 – 1.0 for asphalt and sand) and approximately the same values of k_d, k_s.

Table 10.

Values of shininess coefficient, surface roughness, diffuse and specular reflection coefficients for building materials

Material	n	α	k_d	k_s
Asphalt	5-20	0.5 – 1	0.51	0.49
Brick	5-15	0.3 - 0.7	0.51	0.49
Concrete	5-15	0.3 - 0.5	0.5	0.5
Sand	2-10	0.7-0.9	0.63	0.37

Table 11 [422, 424] shows the values of n, α, k_d, k_s for cellulosic materials. Unpolished wood has a non-smooth surface and, accordingly, high roughness α (0.7 for oak, cherry). The surface of unpolished wood is characterized mainly by diffuse light reflection (k_d is about 0.7 for oak, cherry, pine) and a low value of n (up to 30). Polished wood is slightly more shiny ($n = 50 - 100$ for maple) and have a slight roughness ($\alpha = 0.02 - 0.05$). Paper and cardboard are rough ($\alpha = 0.6 - 0.8$) and diffuse ($k_d = 0.7$) materials.

Table 11.

Values of shininess coefficient, surface roughness, diffuse and specular reflection coefficients for cellulosic materials

Material	n	α	k_d	k_s
Polished maple	50-100	0.02 - 0.05	0.37	0.63
Polished mahogany	40-80	0.02 - 0.05	0.37	0.63
Polished teak wood	30-70	0.02 - 0.05	0.37	0.63
Polished cherry	30-70	0.02 - 0.05	0.37	0.63
Polished oak	30-60	0.02 - 0.05	0.37	0.63
Polished pine	10-40	0.02 - 0.05	0.38	0.62
Maple	10-30	0.3 - 0.6	0.64	0.36
Mahogany	10-30	0.25 - 0.5	0.63	0.37

Continuation of Table 11.

Material	n	α	k_d	k_s
Teak tree	10-30	0.4 - 0.6	0.63	0.37
Cherry	10-30	0.3 - 0.7	0.65	0.35
Oak	10-30	0.2 - 0.7	0.64	0.36
Pine	5-20	0.3 - 0.6	0.65	0.35
Paper	5-20	0.6 - 0.8	0.67	0.33
Cardboard	5-15	0.6 - 0.8	0.72	0.28

Table 12 [422, 424] shows the values of n, α, k_d, k_s for ceramics and glass. The n value for ceramics is relatively small (from 5-20 for earthenware to 30-80 for glazed ceramics). The roughness α of ceramic products is average (0.2-0.4). The coefficient of diffuse k_d reflection is average (0.5-0.6 for glazed ceramics, porcelain) or high (0.8 for earthenware). Pure glass is smooth ($\alpha = 0.02 - 0.05$) and highly shiny ($n = 600 - 1000$, $k_s = 0.98$). At the same time, frosted glass has an average roughness ($\alpha = 0.3 - 0.6$), a large k_d value (0.8) and a relatively small n value (30-100).

Table 12.

Values of shininess coefficient, surface roughness, diffuse and specular reflection coefficients for ceramics and glass

Material	n	α	k_d	k_s
Glazed ceramics	30-80	0.2 - 0.3	0.5	0.5
Porcelain	10-40	0.2 - 0.3	0.6	0.4
Earthenware	5-20	0.2 - 0.4	0.8	0.2
Clean glass	600-1000	0.01-0.05	0.02	0.98
Frosted glass	30-100	0.3-0.6	0.8	0.2

The data in Tables 1-12 are approximate and intended to be used as initial shader parameter values. In the future, these parameters can be more accurately selected depending on the features of the three-dimensional scene.

In general, determining the characteristics of light reflection for each material allows to adaptively choose the appropriate lighting model, taking into account the requirements for performance and realism of scene formation.

Therefore, such parameters as the diffuse reflection coefficient, specular reflection coefficient, surface roughness, surface shininess are taken into account for the color intensity of a pixel calculation. The correctness of the presentation of the optical properties of the surface of the object during rendering depends significantly on the selection of these coefficients. Shiny and smooth materials, such as metals, still liquids, gemstones, are characterized by a large value of the specular reflection coefficient and surface specularity coefficient. Rough and matte materials, such as wood, fabrics, plastics, have large values of the coefficient of diffuse reflection and surface roughness.

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